Microstrip antenna design for arrays generating OAM mm-wave radio signals

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Abstract. The paper is devoted to development of the single antenna as an element of the array, intended for radiating electromagnetic fields with different orders of the orbital angular momentum (OAM) in the band 77 ÷ 78.5 GHz. Multiplexing on OAM provides more opportunities for safe data transmission and increases the quantity of the simultaneously transmitted channels. The antenna design takes into account the special requirements for its structure, imposed by its practical usage in array. The modeling process includes calculating the dimensions, selecting the suitable materials (Rogers RO 3003) and components, simulating with the software and analyzing the following characteristics: VSWR, return loss S_{11}, input impedance, and radiation pattern. The designed antenna represents a half-wave dipole, fed by coplanar waveguide port and matched to 50 Ohm impedance. Its VSWR is less than 1.8, radiation pattern is quite wide. Its configuration and size provide easy combination of such elements in array, including the question of the feeding lines simplicity. The recommendations on the following research steps are given. The application areas are described.

1. Introduction

One of the main tendencies of modern wireless communication lines consists in moving to the high frequency band, which is attractive due to the absence of severe radiation limits and low load of its usage. Particularly W frequency band (W-band, 75-110 GHz) shows the great potential to provide 100 Gbps wireless links using existing technologies. Moreover high frequencies lead to the equipment miniaturization which is very desirable for mobile devices. In the Russian Federation the W-subband 76-78 GHz is determined to be used for mobile applications [1].

Another interesting radio technology is multiplexing the radio signals on the basis of the orbital angular momentum (OAM) of the electromagnetic field, which gives us a new set of basic functions to reduce the overloading of frequency resource and provide high data security.

For the generation of radio beams with non-zero OAM state various designs for transmitting antennas are used: antenna arrays, antennas with a spiral phase plate (SPP) or metasurface plate, etc. Among them SPP is one of the most common solutions. Based on this approach, a flat 8-element antenna array operating at 60 GHz and represented by a multilayer phase-shifting surface is proposed in [2]. To implement phase control between the incoming and outgoing vertically polarized waves the antenna array includes several conductive SPP plates separated with dielectric layers. The main disadvantage of SPP based OAM antennas is that one configuration of the SPP plate corresponds to only one OAM state of emitted radio waves.

The principle of generating OAM radio waves for metamaterial plates is similar to the SPP. The two-layer metamaterial plates are a spatial-variational lattice consisting of rectangular [3] or U-shaped [4] holes. By controlling the spatial orientation angle of the holes the required wave front of emitted radio wave is created.

Another common solution is application of circular antenna arrays, elements of which are fed with the signal of uniform amplitude and different phase. The main advantage of circular antenna arrays over the aforementioned approaches is the possibility of radio waves generation with various OAM states without changing the antenna configuration. In this way an eight-element antenna array operating at a frequency of 2.45 GHz is presented in [5] generating radio waves of $l = \pm 1$, $l = \pm 2$, $l = \pm 3$ OAM states. The main disadvantage of this class of OAM antennas is the need to develop a complex feeding line for the array elements.

In this paper we consider the approach based on circular antenna arrays, since it is more flexible and provides more opportunities for multiplexing channels. To implement this, first of all, the single antenna as an elementary radiator of the array is necessary. The main goals for its development are ability to operate in the band of $77 \div 78.5$ GHz, compactness, simplicity, possessing the low profile and ease for combining in array. According to the given requirements the microstrip antenna was chosen due to its application, low profile, low cost and planar configuration, apart from the ease of patch integration with the high frequency microwave integrated circuits [6].

There are many solutions for microstrip antenna design for W-band. In [7] the rectangular microstrip antenna operating at 76 GHz is presented. Waveguide-microstrip converter is used to couple the energy into the microstrip line to feed the antenna on the substrate. The results of simulation and real test showed that antenna performance is not satisfactory. The analysis of results reveals that microstrip line affects performance of the antenna greatly. A novel corner-fed 45-degree polarized patch array is proposed in [8]. A slot is etched on the patch in order to excite 45-degree polarization. Simulation results show the good performance in W-band.

Although, in order to be applicable for circular antenna arrays designed to generate OAM signals with circular polarization, microstrip antenna must have the linear polarization. Thus, in [5] a square microstrip radiator with truncated angles is used as the element of the antenna array. The circular polarization of the antenna array is due to many factors, such as the size of the antenna, the size of truncated angles, and the position of the feeding port.

The circular patches are also commonly applied for OAM radio waves generation, both as individual transmitting antenna and as the element of antenna array. For example, four circular patches are used to build the OAM-generating array in [9]. To obtain a wideband operation each circular patch is composed of three substrate layers and an air-gap. A combination of a circular patch and 3dB quadrature hybrid circuit is proposed in [10] to generate OAM radio beams with two opposite OAM states. Consequently, the circular patch is believed to be significant to the wireless communication applications due to its simple geometry.

Based on the literature review we can conclude that application of circular antenna arrays for OAM radio signals generation seems to be more promising and convenient in practice, comparing to the other solutions. So in this paper we propose to develop microstrip circular patch antenna, operating in W-band and applicable in array for generating OAM signals.

The paper is organized as follows: in Section II the issues regarding the antenna design and calculation are described. The simulation results are presented and discussed in Section III. The conclusions and future workare presented in Section IV.

2. Microstrip antenna design

There are few requirements for the antenna used as a radiator of the array. First of all it should work in the desired band ($77 \div 78.5$ GHz in our case). Its radiation pattern should be wide, more than 180°, and the gain – no less than the gain of the dipole antenna. It should be characterized by the linear polarization. And finally the construction of the antenna should provide miniaturization and simplicity of its application in array.

In this paper we propose to consider the circular patch antenna as a basis for designing the other antennas, since its simple structure provides wide frequency band and wide radiation pattern. Since its shape will be transformed, so the basic scheme of the advanced circular patch is presented at figure 1.

The antenna represents a microstrip half-wave radiator, which characteristic impedance is matched to 50 Ohm. Since the band 77÷ 78.5 GHz was chosen, then Rogers RO 3003 laminate was applied for the antenna design: substrate thickness: 0.5 mm; foil thickness: 35 μm; dielectric constant: 3.00±0.04; the dielectric loss tangent: 0.0010. The antenna is fed by coplanar waveguide port and the KMCO KPC100 connector, operating till 110 GHz. The main part of the radiating element is composed from a circle, which radius is 2.2 mm. The total size of the antenna is 9.6 × 4.8 mm (figure 1). The following settings were made for calculation: frequency range – 76.5 ÷ 79 GHz, boundaries – open space.

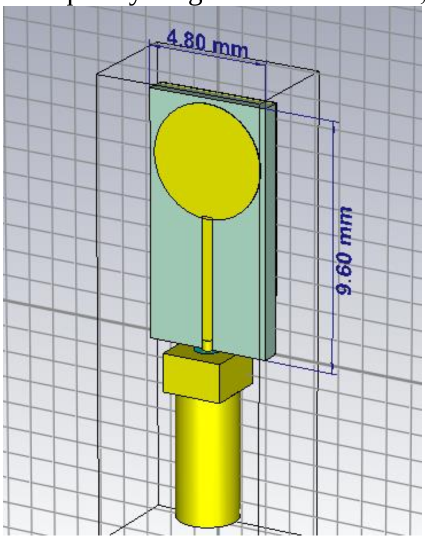

Figure 1. The antenna view.

3. Simulation results

Let us analyze the main obtained antenna's characteristics. The return loss S_{11} dependence is shown at figure 2, where its values are less than -10 dB in the band 76.5 ÷ 79 with the resonance at 78.395 GHz. That means that the antenna is well matched in the most part of the operating band.

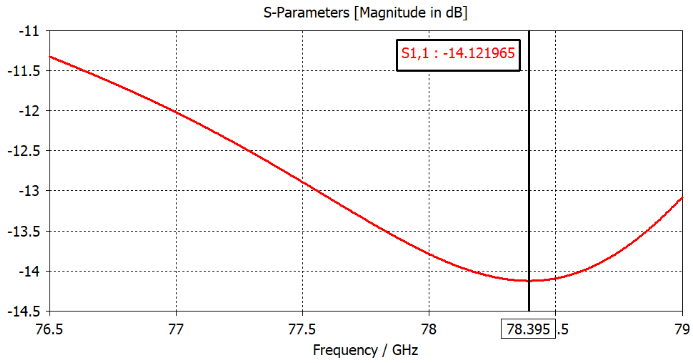

Figure 2. The return loss of the developed antenna.

Radiation pattern (RP) of the designed antenna is shown at figure 3. Since it's wide, so this feature is good for forming the array RP. Although the realized gain taking mismatch into account is -0.604 dB it can be increased by combination of small antennas with the corresponding array factor and application of matching devices.

Also the other characteristics, such as real and imaginary parts of the input impedance, VSWR were calculated. The currents distribution was also constructed and analyzed. Summarizing, we can say that the antenna is operating in the required frequency band, has a wide radiation pattern and can be further considered in array for generating OAM signals. It should be also mentioned that the described antenna can be a good prototype for other modifications that will be investigated later.

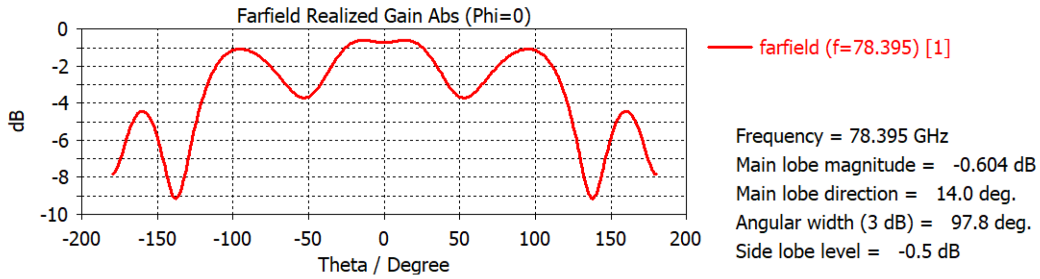

Figure 3. Radiation pattern of the developed antenna.

4. Conclusions

In this paper we proposed the small microstrip antenna on the basis of the advanced circular patch for the antenna array, forming radio signals with the given order of OAM. The antenna configuration was calculated via mathematical and computer modelling, and the simulation results are presented. Particularly, return loss S_{11}, VSWR, input impedance, radiation pattern and currents distribution were calculated and analyzed. By changing some geometrical parameters of this prototype several configurations can be designed and applied in array.

The antenna also provides opportunities for miniaturization of the whole array and equipment and costs reduction. Its features allow expanding the possibilities of modern and future communication systems, such as Radio-over-Fiber and Internet of things networks. In total multiplexing on OAM will increase the capacity and noise immunity of these networks along with improving the efficiency of usage and expanding the service area.

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